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Equilibrium and non-equilibrium condensation phenomena in tuneable 3D and 2D Bose gases

Zoran Hadzibabic
THE CHANCELLOR, MASTER AND SCHOLARS OF THE UNIVERISTY OF CAMBRIDGE

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We have investigated a range of equilibrium and non-equilibrium many-body phenomena, trapping ultracold atomic gases in different geometries including both 3 and 2 spatial dimensions, and with both the conventional harmonic trap and a newly-developed "box trap". With the 3d harmonic trap, we observed a new "superheated Bose-condensed gas" which remains condensed above the expected critical temperature, and performed one of the first studies of the strongly-interacting "unitary" Bose gas. With the 2d harmonic trap we showed how the interaction-driven BKT phase is connected with purely statistical theory, and with the 3d box trap we created the world's first atomic BEC in a quasi-uniform potential.

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Final report for Grant FA8655-12-1-2131

"Equilibrium and non-equilibrium condensation phenomena in tuneable 3D and 2D Bose gases"

PI: Zoran Hadzibabic, University of Cambridge

Grant period: September 1, 2012 – August 31, 2015

Supported by this grant we have investigated a range of equilibrium and non-equilibrium many-body phenomena with ultracold atomic gases trapped in different geometries, including both 3 and 2 spatial dimensions, and both the "conventional" ultracold-atom setting of a harmonic trap and a newly developed "box trap".

The grant has been extremely successful and has so far resulted in 8 papers, including 1 Science, 1 Nature Physics, 4 Physical Review Letters (PRLs), and 1 Physical Review A. One more project has been completed in the last months of the grant and the paper is currently being drafted. Our work has also attracted various press coverage, such as editorial and news articles in Science, Nature, Physics, and Physics Today. It has also led to invited talks at all the main conferences in the field of ultracold atoms and more generally in the fields of atomic and condensed matter physics, including the International Conference on Atomic Physics (ICAP), the biennial BEC Conference ("Frontiers in Quantum Gases") in Sant Feliu, DAMOP and the APS March Meeting.

Our results can be divided into three categories, according to the geometry in which the ultracold atoms were trapped:

(I) "Conventional" 3D harmonic trap

In this setting we have performed two non-equilibrium experiments, exploiting the fact that in a gas of ^{39}K atoms we can dynamically tune the strength of inter-particle interactions:

First, we have observed and quantitatively explained a new non-equilibrium state of matter – a "superheated Bose-condensed gas" which remains condensed far above the equilibrium critical temperature when the interaction strength in the gas is tuned to very low values [1]. We have experimentally reconstructed and theoretically explained the non-equilibrium phase diagram of this system. Beyond purely scientific interest, this work points to a possible way to extend the coherence time of atomic BECs by up to a minute, which could have practical implications for precision measurements and quantum information processing.

Second, we performed one of the first studies (alongside Christophe Salomon's group at ENS Paris and Eric Cornell & Debbie Jin's group at JILA) of the "unitary" Bose gas [2], in which the interactions are as strong as theoretically allowed by quantum mechanics, i.e. the *s*-wave scattering length is tuned to infinity using a Feshbach resonance. The unitary Fermi gas has been one of the most actively researched ultracold-atom systems in the past decade, in particular due to its connections to the BEC-BCS crossover and (possibly) high-temperature superconductivity. In comparison, the unitary Bose gas is essentially unexplored, but promises to be as interesting. The main reason for this delay in the studies of the unitary Bose gas is that this state is very short-lived, due to enhanced inelastic three-body processes that lead to both particle loss and heating, and it is actually still not fully understood whether even in principle it has well defined equilibrium properties. In our work, we studied the stability of a thermal ^{39}K Bose gas across a broad Feshbach resonance, and directly measured for the first time the general scaling laws relating the particle-loss and heating rates to the temperature,

scattering length, and atom number. Moreover, we identified ^{39}K as a promising candidate for future studies of the equilibrium Bose gas at unitarity.

(II) 2D harmonic trap

We have realised a 2D harmonically trapped ^{39}K gas with tuneable interactions, and have performed measurements of the critical point for a transition to superfluidity as a function of the coupling strength. As originally predicted in the grant proposal, our measurements have explicitly shown how the interaction-driven Berezinskii-Kosterlitz-Thouless (BKT) phase transition is smoothly connected and unified with the purely statistical BEC transition in the limit of vanishing interactions [3].

(III) 3D Box trap

We have created the world's first atomic Bose-Einstein condensate in a (quasi-)uniform potential, by trapping atoms in an "optical box" trap [4]. This solved a long-standing problem in the field of ultracold atoms, and opened numerous new possibilities for studying many-body physics in a "textbook" setting, without the additional complications of the gas inhomogeneity due to a harmonic trapping potential. Specifically, it eliminated the need to rely on the local density approximation, which is particularly important for studies of critical behaviour near a phase transition, where the correlation length in the system diverges. Several other leading groups (including Jean Dalibard's group in Paris, Cheng Chin's group in Chicago, and Martin Zwierlein's group at MIT) have since started working on similar uniform systems. In our group we have already performed four further experiments using this novel trap:

In [5] we studied the thermodynamics of a partially Bose-condensed gas and experimentally observed for the first time the quantum version of the famous Joule-Thomson cooling effect (the classical version of which is widely exploited in industrial refrigeration), which was theoretically predicted 75 years earlier.

In [6] we have performed a comprehensive study of the ground state properties of the BEC in a uniform potential, including measurements of the interaction energy, coherence properties, and the dynamics of free expansion of the BEC released from the box trap. In particular we have explicitly demonstrated the Heisenberg-limited momentum spread of a fully coherent BEC for a range of different box sizes.

So far the most important paper based on our box potential is on the non-equilibrium dynamics of Bose-Einstein condensation in a temperature-quenched homogeneous gas [7]. This experiment provided the most direct confirmation (in any physical system) of the Kibble-Zurek theory of the dynamics of spontaneous symmetry breaking, which is relevant for a wide variety of physical systems and has implications as far reaching as understanding the formation of large structures in the early universe.

Finally, we have recently completed measurements on the emergence of quantum turbulence in a periodically driven deeply degenerate Bose gas. This is another major topic that could not be properly addressed using the standard harmonic trap for ultracold atoms. Both classical and quantum turbulence have been studied in a wide variety of physical systems (from classical gases and water to superfluid helium) for many years. However, a system in which experiments could be directly and reliably compared with theoretical calculations has been lacking. We have now demonstrated such a system, observing good agreement between our measurements and numerical simulations. The paper on this work is currently being drafted and should be published in 2016.

Already published papers supported by this grant:

[1] **A Superheated Bose-Condensed Gas**
A. L. Gaunt, R. J. Fletcher, R. P. Smith, and Z. Hadzibabic,
Nature Phys. **9**, 271 (2013).
DOI: 10.1038/nphys2587
Featured in Nature Physics “News & Views” and a Phys.org news story

[2] **Stability of a Unitary Bose Gas**
R. J. Fletcher, A. L. Gaunt, N. Navon, R. P. Smith, and Z. Hadzibabic,
Phys. Rev. Lett. **111**, 125303 (2013).
DOI: 10.1103/PhysRevLett.111.125303

[3] **Connecting Berezinskii-Kosterlitz-Thouless and BEC Phase Transitions by Tuning Interactions in a Trapped Gas**
R. J. Fletcher, M. Robert-de-Saint-Vincent, J. Man, N. Navon, R. P. Smith, K. G. H. Viebahn, and Z. Hadzibabic,
Phys. Rev. Lett. **114**, 255302 (2015).
DOI: 10.1103/PhysRevLett.114.255302
Featured in PRL Editors’ Suggestions

[4] **Bose-Einstein Condensation of Atoms in a Uniform Potential**
A. L. Gaunt, T. F. Schmidutz, I. Gotlibovych, R. P. Smith, and Z. Hadzibabic,
Phys. Rev. Lett. **110**, 200406 (2013).
DOI: 10.1103/PhysRevLett.110.200406
Featured on the cover of PRL, in PRL Editors’ Suggestions, Physics “Synopsis”, Nature “Research Highlights”, Science “Editors’ Choice”, and a Physics World news story

[5] **Quantum Joule-Thomson Effect in a Saturated Homogeneous Bose Gas**
T. F. Schmidutz, I. Gotlibovych, A. L. Gaunt, R. P. Smith, N. Navon, and Z. Hadzibabic,
Phys. Rev. Lett. **112**, 040403 (2014).
DOI: 10.1103/PhysRevLett.112.040403
Featured in Physics Today

[6] **Observing properties of an interacting homogeneous Bose-Einstein condensate: Heisenberg-limited momentum spread, interaction energy, and free-expansion dynamics**
I. Gotlibovych, T. F. Schmidutz, A. L. Gaunt, N. Navon, R. P. Smith, and Z. Hadzibabic,
Phys. Rev. A **89**, 061604(R) (2014).
DOI: 0.1103/PhysRevA.89.061604

[7] **Critical dynamics of spontaneous symmetry breaking in a homogeneous Bose gas**
N. Navon, A. L. Gaunt, R. P. Smith and Z. Hadzibabic,
Science **347**, 167 (2015).
DOI: 10.1126/science.1258676
Featured in Science “Perspectives”